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Grazing decreased water use efficiency in Central Asia from 1979 to 2011

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ABSTRACT

Accurate predictions of water vapor at large temporal and spatial scales are particularly important in global studies. In recent years, Central Asian grasslands have been subject to both intensive grazing and variability in climatic conditions. However, uncertainties about grazing on water cycling under climate change still exist. Therefore, the Biome-BGC grazing model was applied to assess the effects of grazing on evapotranspiration (ET) and water use efficiency (WUE). Three grassland types were studied during the period 1979–2011: forest meadow (FM), temperate grassland (TG) and desert grassland (DG). ET shows a gradual decreasing trend from FM (365.65 ± 36.86 mm m^{-2} yr^{-1}) to DG (183.32 ± 21.15 mm m^{-2} yr^{-1}), and WUE ranging from 0.62 ± 0.03 g C kg^{-1} H_2O in FM to 1.12 ± 0.10 g C kg^{-1} H_2O in TG, with an average of 0.83 ± 0.05 g C kg^{-1} H_2O. Although there was a significant decrease in ET of 1.47–2.72 mm m^{-2} yr^{-1}, WUE increased at a rate of 0.004 g C kg^{-1} H_2O yr^{-1} in Central Asia. From 1979 to 2011, grazing lowered ET by 7.47% in Central Asia; the reduction rates for FM, TG and DG were 3.10%, 12.70% and 7.42%, respectively. In general, grazing decreased WUE by 3.60%. From non-grazed to grazed scenario, WUE increased by 6.86% for FM, but WUE decreased by 7.27% and 5.61% for TG and DG. An over-compensation of GPP under grazing might account for the higher WUE under certain grazing intensities. In order to achieve maximum utilization of water efficiency, proper grazing intensity for TG, DG and FM should be limited to 0.17, 0.39 and 0.38 head/ha, respectively.

1. Introduction

In global climate studies, it is particularly important to be able to accurately predict the exchange of water vapor and carbon dioxide between the atmosphere and terrestrial ecosystems, over both long periods of time and over large areas (Li et al., 2006). Evapotranspiration (ET) is water vapor exchange between the atmosphere and terrestrial ecosystems and, notwithstanding precipitation, ET forms one of the largest parts of the overall hydrological budget (Brutsaert, 1982). Closely linked to ET are the growth of vegetation and possible future photosynthetic carbon (C) uptake (Brümmer et al., 2012). Water use efficiency (WUE) is the ratio of photosynthetic carbon taken up per unit of water loss by transpiration (Cowan and Farquhar, 1977). Therefore, the study of ET and WUE among a variety of terrestrial ecosystems is therefore fundamental to understanding their role in local, regional and global water cycles and water vapor exchange between the Earth's surface and the atmosphere.

ET and WUE are controlled by canopy architecture and development, soil characteristics, and a variety of in situ environmental variables (Bremer et al., 2001; Hupet and Vanclooster, 2005). Human activities, as, for example, large-scale changes in land cover and land use, will affect ET in a variety of ways. These may include modifications to surface roughness length, the amount of vegetation covering the land and moisture in the soil (Alfieri et al., 2007; Hidy et al., 2012; Lapitan and Parton, 1996; Li et al., 2006).

A great part of Central Asia is characterized by semiarid or arid climate which is fragile and sensitive to both changes in climate and anthropogenic disturbances (Kerven et al., 2011). Of the land-use practices in grasslands in this region, grazing is the most frequently encountered (Polley et al., 2008). Grazing removes green leaf area and changes the microclimate of the surface which may affect ET and WUE (Li et al., 2000; Luo et al., 2010; Song et al., 2014). To cite an example, Cattle (*Bos taurus*) spring grazing a tallgrass prairie site reduced season-long ET by 6.1% compared with an ungrazed site (Bremer et al., 2001). Likewise, the Northern Great Plains semiarid grasslands of the US exhibited a three-year average ET that was 7% less when it was grazed than when left ungrazed (Frank, 2003). On the other hand though, another study reported heavy grazing by prairie dogs actually increased

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ET when compared to a lightly grazed site (Day and Detling, 1994). Additionally, Stewart and Verma (1992) reported no differences in ET from grazing in a tallgrass prairie even when leaf area index (LAI) differences were large and soil water was nonlimiting (Stewart and Verma (1992). While the effects of grazing on water cycles are related to vegetation cover, energy availability and soil water conditions, uncertainties regarding these effects still exist.

Therefore, the Biome-BGC grazing model was applied in this study to assess ecological effects of grazing on the grasslands in central Asia under climate change, specifically, (1) characterize the spatial and temporal dynamics of the actual ET and WUE from 1979 to 2011 among different grassland types; (2) analyze how and to what extent does grazing affect grassland ET and WUE. This quantification can provide a reference for maintaining dry grassland stability and improving resistance to potential climate changes.

2. Data and methods

2.1. Study area

Our study area includes five republic countries of Central Asia (i.e., Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) and Xinjiang in China, occupying an area of nearly 5.7 million km^2 and have low precipitation, high evapotranspiration, arid and semi-arid climate (Cowan, 2007). Precipitation decreases toward the center and south of Aral Sea, and increases toward the north, east, and southern edges of the region (Buslov et al., 2007). Grasslands fall into one of three different bio-geographic types along the vertical gradients; forest meadow (FM) was obtained when the elevation above 1650 m a.s.l. and depending on the climate, grassland below 1650 m a.s.l. was further subdivided into desert grassland (DG) and temperate grassland (TG). Grassland production in northern Kazakhstan was more determined by temperature than precipitation so this region was classified as TG. Southern Kazakhstan and the desert areas of Xinjiang suffer from a deficiency of water and were therefore classified as DG (Luo et al., 2012). 63% of this land area are rangelands with an arid climate. The vast rangelands of Central Asia form the world's largest contiguous area of grazed land. (Fig. 1).

2.2. Biome-BGC grazing model

Biome-BGC is a biogeochemical model that simulates above- and belowground carbon, water, and nitrogen cycles of different vegetation types (Running and Hunt, 1993; Thornton, 1998). For the water cycle, Biome-BGC calculates transpiration, interception and evaporation from the canopy, soil water content, snowmelt and outflow from the soil. For carbon cycles, the model calculates photosynthesis, growth respiration, maintenance respiration, allocation, litter-fall and decomposition. Finally, nitrogen cycling is represented by deposition, uptake, litter-fall and mineralization.

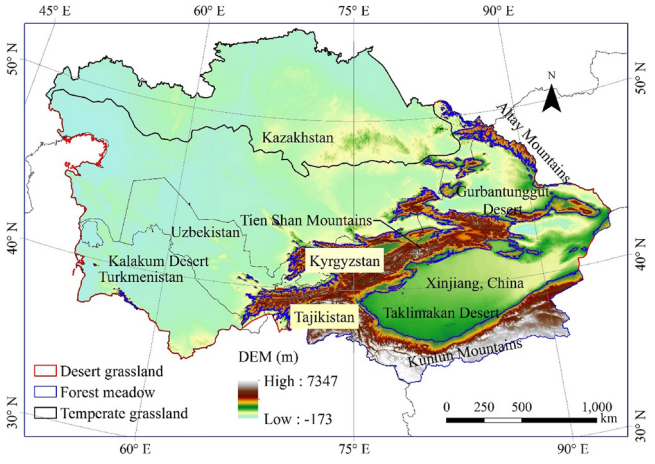

Fig. 1. Study area and distribution of major grassland types in Central Asia.

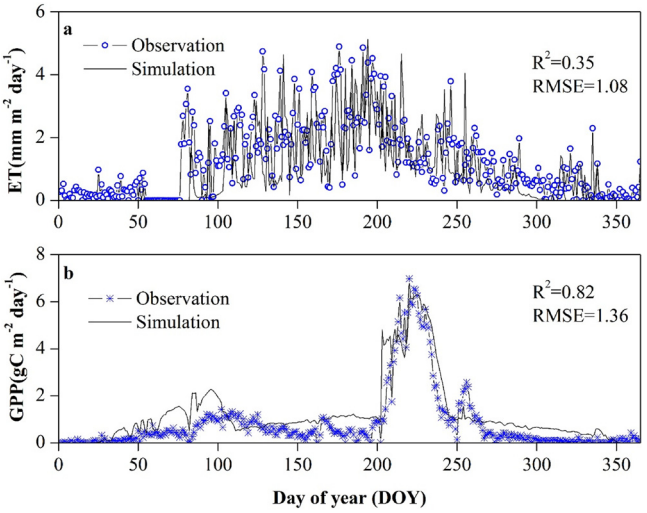

Fig. 2. Comparison of observed and simulated ET (a) and GPP (b).

The original model has been recently modified to improve its performances when applied to grassland with herbaceous. A defoliation formulation developed by Seligman et al. (1992) was integrated into the Biome-BGC model (Luo et al., 2012), resulting in a Biome-BGC grazing model which describes the effects of grazing on the carbon cycle of grassland ecosystems. Han et al. (2016) give a detailed description of this model. In this model, Net Primary Productivity (NPP) is defined as the summation of the Gross Primary Productivity (GPP), autotrophic respiration (Ra) and defoliation rates (Dr).

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{Ra} - D_r \quad (1)$$

$$D_r = G_e \times GI \times (C_{leaf} - (C_{leaf})_r) \quad (0 < D_r < G_i D_x) \quad (2)$$

where D_r is the defoliation rate (g C ha^{-1} d^{-1}), Ge is the grazing efficiency of the livestock (ha/d/sheep unit), GI is the grazing intensity (head/ha), C_{leaf} is the C in the leaf biomass (g C m^{-2}), $(C_{leaf})_r$ is the residual aboveground C_{leaf} that is unavailable to livestock (g C m^{-2}), and D_x is the satiation consumption rate of the livestock (g C d^{-1} head^{-1}) (NRC, 1985).

WUE is defined as the ratio of GPP to ET, i.e. the amount of carbon assimilated per unit of water loss by ET:

$$WUE = GPP/ET \quad (3)$$

2.3. Input datasets

Minimum and maximum air temperature, precipitation, solar radiation and vapor pressure deficit were some of the daily climate data required. These, along with other general information on the stands being studied, such as latitude, soil depth, soil water content, were then imported into the model. In addition to this, about 50 parameters describing the eco-physiological behavior of the species found in the forest stands were similarly required (Running and Hunt, 1993). Meteorology data was gathered over Central Asia on a daily basis from 1979 to 2011 and displayed on a grid at a resolution of 0.5 of latitude/longitude. The information originated from the Climate Forecast System Reanalysis (CFSR) (Environmental Modeling Center, 2010). By using linear interpolation for 1979 to 2011 and livestock numbers for the different regions based on FAO grazing intensity data for the year 2000, grazing data over this time period were obtained (Wint and Robinson, 2007). The grazer species including cattle, buffalo, sheep and goats according to Central Asian' husbandry situation. All the grazers

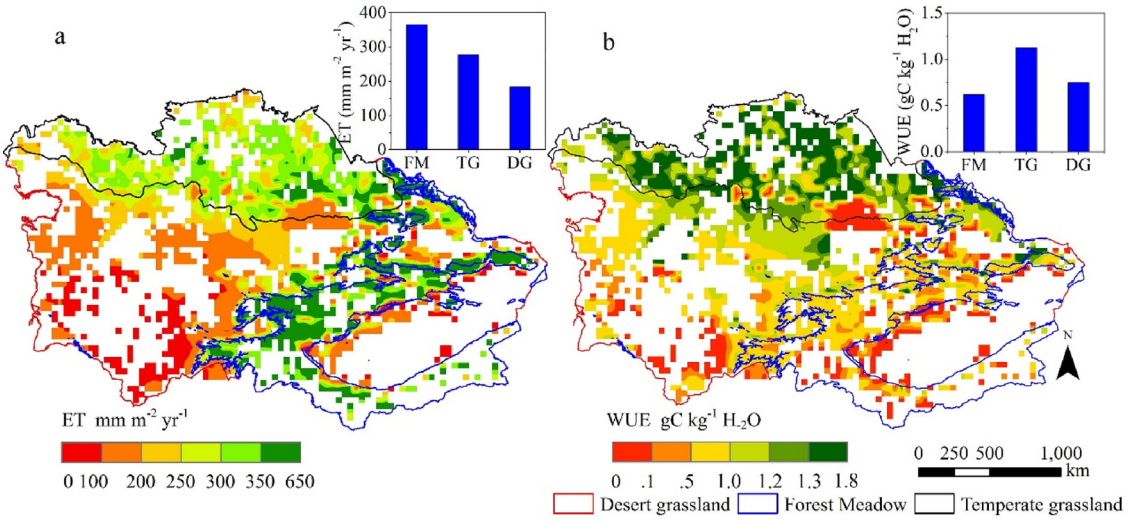

Fig. 3. Spatial distribution of average annual actual evapotranspiration from 1979–2011. FM represents forest meadow, TG represents temper grassland, and DG represents desert grassland.

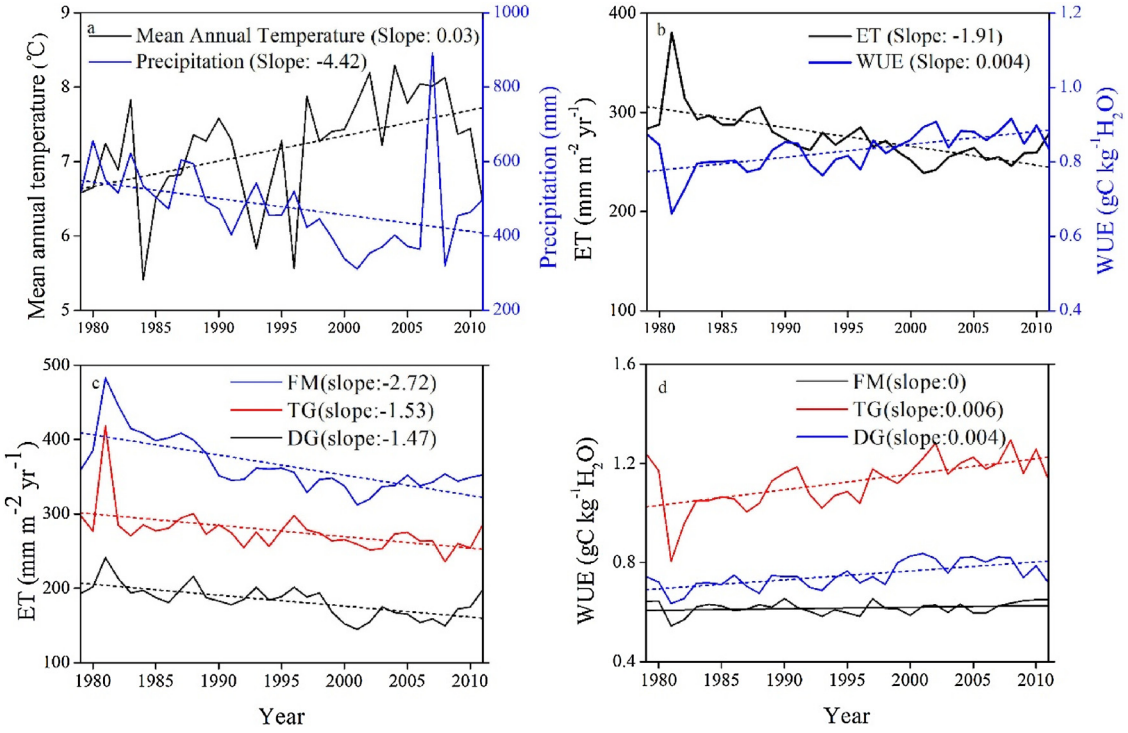

Fig. 4. Inter-annual variation of (a) annual climate and (b, c, d) ET/WUE over Central Asian grasslands from 1979 to 2011. FM represents forest meadow, TG represents temper grassland, and DG represents desert grassland.

are calculated into sheep unit according to the "animal unit equivalent" standard provided by Ministry of Agriculture of the People's Republic of China (http://www.chinaforage.com/standard/zaixuliang.htm). One cattle equals to 6.0 sheep, one buffalo equals to 6.5 sheep and one goats equals 0.9 sheep. Atmospheric CO_2 concentrations for 1979–2011were obtained from observations taken at Mauna Loa (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt). Site conditions included soil texture, elevation, and latitude. The Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) was instrumental in giving information on soil texture data, including sand/silt/clay percentages and effective soil depth.

2.4. Model validation and simulation design

To validate the model, a comparison was made between the simulated ET values and the available 2013 actual values. The site chosen was located in Yongfeng (43.68 °N, 87.33 °E) southwest of the city of Urumqi, Xinjiang, China. Prior to the observation period, the site had been intensely grazed, with only about 60% exhibiting patchy clumps of vegetation and the rest bare soil. Energy balance measurements were conducted using the Bowen ratio energy balance (BREB) system (Model 023/CO_2 Bowen ratio system, Campbell Sci., Logan, UT, USA). Each site included one BREB system (tower) able to retrieve data a minimum of 200 m in all directions.

Since WUE was calculated as the ratio of GPP to ET, validation of WUE can be explained by comparing the simulated and observed GPP.

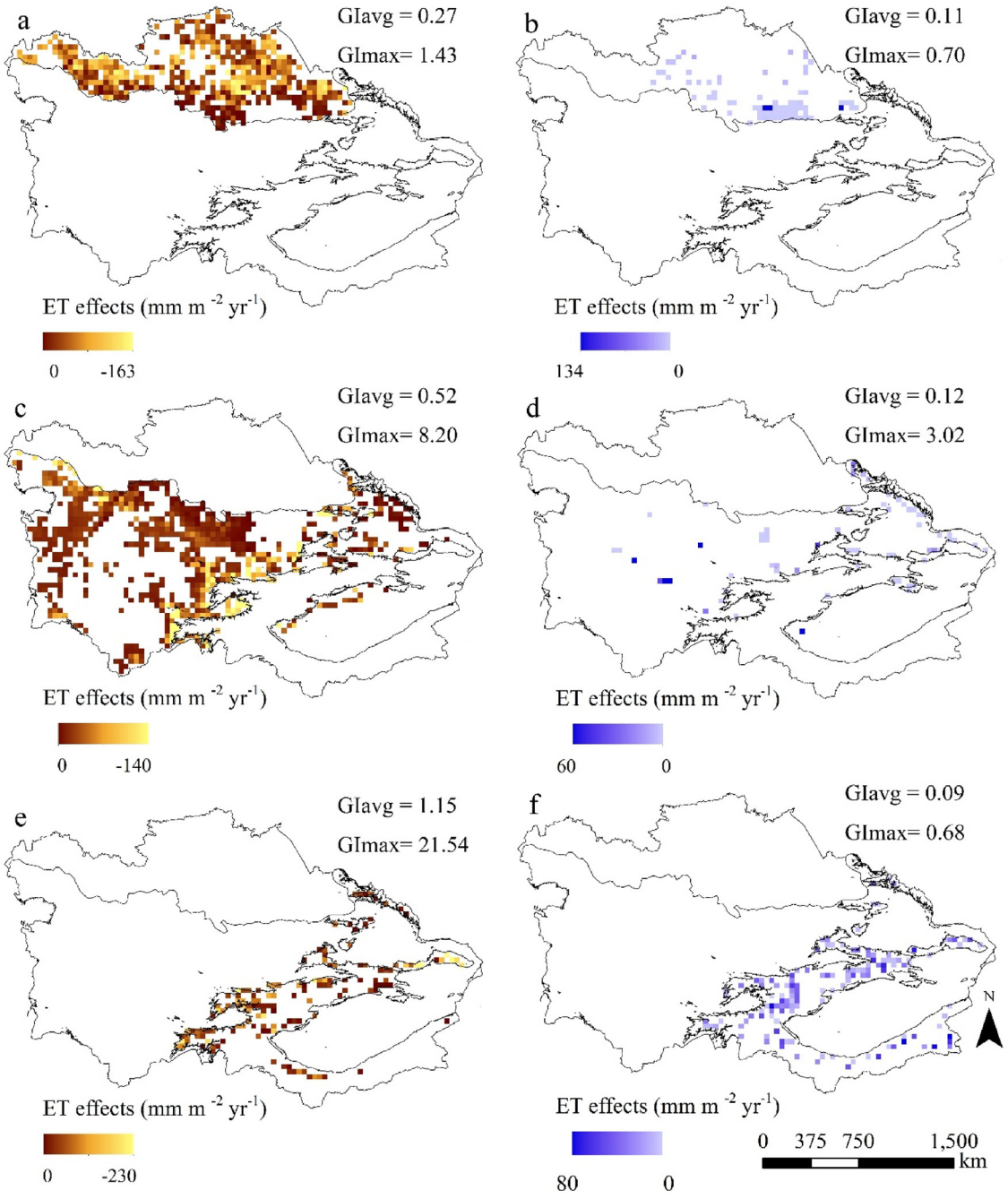

Fig. 5. Spatial difference between ET before and after grazing from 1979 to 2011 for different grasslands. a) temperate grasslands (TG) with decreased ET, b) temperate grasslands (TG) with increased ET, c) desert grasslands (DG) with decreased ET, d) desert grasslands (DG) with increased ET, e) forest meadow (FM) with decreased ET, f) forest meadow (FM) with increased ET. GImax: maximum grazing intensity for grazing effects; GIavg: averaged grazing intensity for grazing effects.

Besides, due to the scarce of eddy covariance data in Central Asia, flux data from another sites with similar ecological environment in Kendall grassland was downloaded to validate GPP (ftp://cdiac.ornl.gov/pub/ameriflux/data).

After standardizing the input data, the model was set to run a spin-up simulation which start with very low initial levels of carbon and nitrogen state until the total carbon levels stabilize for 6000 years without grazing. Then the Biome-BGC grazing model simulations were run to illustrate two different scenarios -"Grazing" and "Non-grazing". In the "Grazing" scenario, all variables relating to both climate change and grazing were permitted to fluctuate during the complete simulation. For the "Non-grazing" scenario, which considers the impact of climate on carbon dynamics, we used historical climate data but without grazing information for the simulation. Impacts of grazing on carbon dynamics from 1979 to 2011 were obtained using differences between "Grazing" and "Non-grazing" simulations.

3. Results

3.1. Model validation

Fig. 2a depicts the results of ET on a daily basis as measured by the Bowen ratio and the Biome-BGC model in 2013. The results indicated that the observed ET was 0.84 mm m^{-2} day^{-1} while the modeled value was 1.12 mm m^{-2} day^{-1} in average. The difference between the observed and simulated ET ranged from 0 mm to 10.36 mm m^{-2} day^{-1},

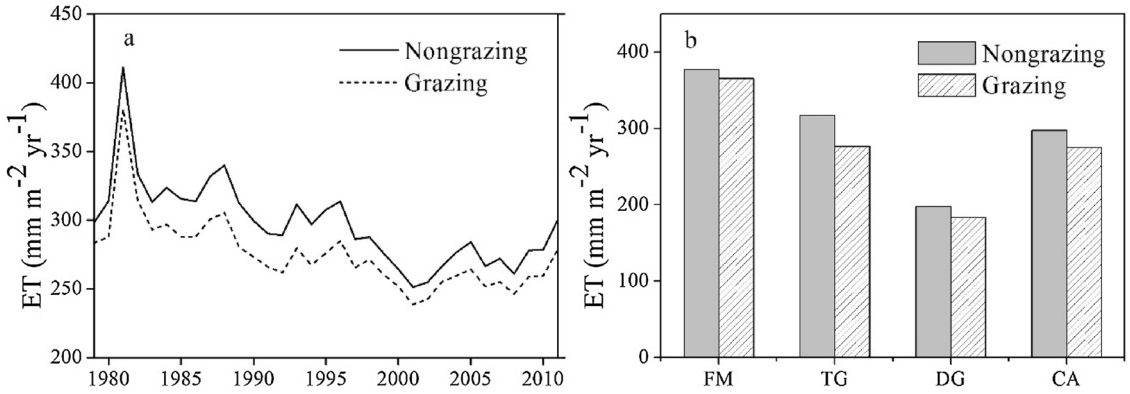

Fig. 6. Comparison of ET under "Non-grazing" and "Grazing" scenarios in Central Asia between 1979 and 2011.

with the RMSE of 1.08 mm, which is quite acceptable. There was a large data gap for DOY 55–73 because Bowen ratio data were missing during this period. As shown in Fig. 2b, Biome-BGC also well simulated GPP for grazed grassland in comparison with the eddy covariance data ($R^2 = 0.82$, $p < 0.05$). In addition, the annual variability in GPP was captured by the model.

3.2. Spatal-temporal distribution of ET and WUE in Central Asia

ET gradually decreases from FM (365.65 ± 36.86 mm m^{-2} yr^{-1}) to DG (183.32 ± 21.15 mm m^{-2} yr^{-1}) as shown in Fig. 3a. As would be expected, this decreasing trend accurately reflected the mountain–oasis–desert ecosystem distribution. On the spatial scale, the highest ET values were distributed in the Qilian Mountain area. This was due to the occurrence of summer and autumn precipitation, higher than in any other regions with an average of about 365.66 mm. In the arid zones, water consumed in ET was mainly from precipitation. It was in the Qilian Mountains, with good sources of water, excellent water conditions, ample vegetative cover plus shallow groundwater levels and wide snow cover that the highest ET in the basin was measured. Temper grassland in Kazakhstan, with an average of 276.93 ± 29.36 mm, also had a relatively strong ET. This was due to irrigation in the northern part of Kazakhstan. On the other hand, the lowest ET value, with an average of 183.32 ± 21.15 mm, was found in the lower reaches. This was due to the area suffering from perennial drought and minimal vegetation coverage.

The mean annual WUE of Central Asia's grassland ecosystems, over the period 1979–2011, also showed large spatial variability (Fig. 3b). WUE of the three grassland ecosystems ranged from 0.62 ± 0.03 g C kg^{-1} H_2O in FM to 1.12 ± 0.10 g C kg^{-1} H_2O in TG, with an average of 0.83 ± 0.05 g C kg^{-1} H_2O. TG in northern Central Asia had the highest annual WUE (averaged 1.12 ± 0.10 g C kg^{-1} H_2O). These regions have relatively high net primary productivity (NPP) and evapotranspiration (ET) due to suitable temperatures and ample precipitation. The FM had the lowest annual WUE (averaged 0.62 ± 0.03 g C kg^{-1} H_2O) because of the high ET. Although the annual mean ET was low in DG, low GPP associated with sparse vegetation and low temperature in this region resulted in lower annual WUE (averaged 0.75 ± 0.05 g C kg^{-1} H_2O).

Fig. 4c illustrates the annual ET values from 1979 to 2011 in three grassland areas throughout Central Asia. All grasslands exhibited similar ET but with noticeable annual decline trend ($P < 0.05$). Central Asia experienced significant declines, due to climatic factors, of 1.47–2.72 mm per decade during the 33-year period. From 1979–2011, Central Asia witnessed significant warming (0.3 °C per decade) and a dramatic decrease in precipitation (4.42 mm yr^{-1}) (Fig. 1a). The drier and warmer climate exacerbated the xeric conditions in Central Asia's grasslands and took a toll on the regional ET.

In Central Asia during the period 1979 to 2011, WUE ranged from 0.92 ± 0.55 g C kg^{-1} H_2O in 2008 to 0.66 ± 0.54 g C kg^{-1} H_2O in 1981 (Fig. 4d). Annual WUE increased at a rate of 0.004 g C kg^{-1} H_2O yr^{-1}. In TG, annual WUE increased at a slightly higher rate (0.006 g C kg^{-1} H_2O yr^{-1}), while in DG, WUE also trended upward at a rate of 0.004 g C kg^{-1} H_2O yr^{-1}. No statistically significant trend, however, was observed in FM. (Fig.4d).

3.3. Grazing effects on ET and WUE

A comparison of ET under grazed and non-grazed conditions for different grassland types is shown in Figs. 5 and 6. Notably, ET reductions and increases occurred in all grassland types, depending on the climate conditions and grazing intensity. Approximately 85.77% of TGs showed a decreasing trend in ET because of the more aggressive grazing, which averaged 0.27 head/ha (Fig. 5a). ET increased when the grazing intensity decreased to 0.11 head/ha, but this only accounted for 14.23% of TGs. The same results were observed in DGs; 91.66% of the grasslands experienced ET reduction when the grazing intensity averaged 0.52 head/ha (Fig. 5c). Notably, the grazing intensity in some FM regions was only 0.09 head/ha.; 48.01% of the grasslands showed ET trending upward (Fig. 5f). These results imply that ET might respond to GI differently for different grassland types.

Fig. 6 shows carbon dynamics from the "Grazing" and "Non-grazing" scenarios, representing situations with and without grazing over time. From 1979 to 2011, grazing lowered ET by 7.47% in Central Asia. The reduction rate for FM, TG and DG were 3.10%, 12.70% and 7.42%, respectively.

The grasslands manifested differing patterns of WUE depending on how intensely they were grazed (Fig. 7). Apart from FM, where WUE was positively correlated with grazing intensity (Fig. 7e, f), other areas significantly decreased WUE due to grazing but the rate of decrease varied with grazing intensity. WUE of FM increased by 6.86% from non-grazed to grazed scenario, while WUE of TG and DG decreased by 7.27% and 5.61%. This was resulted from GPP incensement of FM (2.41%) and reduction in TG and DG (18.68% and 11.27%, respectively, Fig. 7d). Spatially, most of the DGs (75.65%) showed a decreasing trend in WUE, because of the higher average grazing intensity of 0.51 head/ha (Fig. 7c). The ET increased when the grazing intensity decreased to 0.39 head/ha, but this only accounted for only 24.35%. On the other hand, WUE of most FMs (88.08%) increased because of GPP increases in this region. Accordingly, 54.22% of DGs experienced WUE increases and the other half decreases. In general, grazing decreased WUE by 3.60% in Central Asia from 1979 to 2011. To ensure the best grazing intensity, TG, DG and FM should be limited to 0.17, 0.39 and 0.38 head/ha, respectively, in order to achieve the maximum utilization of water efficiency.

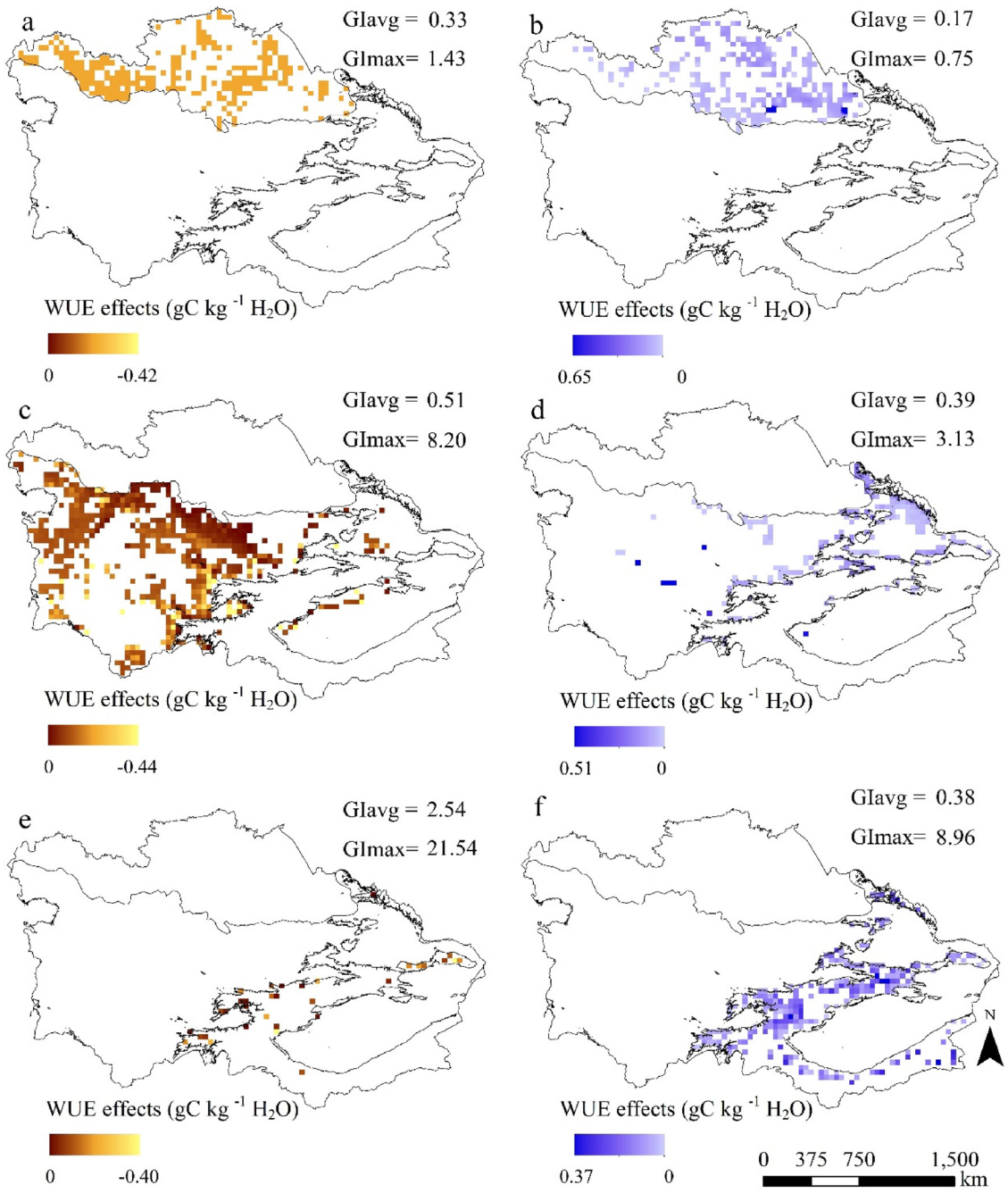

Fig. 7. Spatial difference between WUE before and after grazing from 1979 to 2011 for different grasslands. a) temperate grasslands (TG) with decreased WUE, b) temperate grasslands (TG) with increased WUE, c) desert grasslands (DG) with decreased WUE, d) desert grasslands (DG) with increased WUE, e) forest meadow (FM) with decreased WUE, f) forest meadow (FM) with increased WUE. GImax: maximum grazing intensity for grazing effects; GIavg: averaged grazing intensity for grazing effects.

4. Discussion

4.1. Model performance and uncertainties

The Biome-BGC-grazing model has been shown to accurately predict Central Asian grassland ET on a daily basis. Uncertainties may still remain due to interpretation of the data, both temporal and spatial, even though the sources of the data have been thoroughly vetted. The model was parameterized with limited sites, so some uncertainties may come from the model parameters. For example, water vapor pressure deficit for stomatal conductance were presented as a given for each functional type of plant. These uncertainties in the structure of our model may also be responsible for compromising our simulation results to a certain extent. Future improvements on these aspects of modeling will certainly reduce such uncertainties.

4.2. ET and grazing effects

In our study, ET gradually decreases from the forest meadow (365.65 mm m^{-2} yr^{-1}) to desert grassland (183.32 mm m^{-2} yr^{-1}). The magnitudes and range of variations in ET are consistent with previous research. Zhang et al. (2014) measured ET over the riparian shrub on the Qinghai–Tibet Plateau, and the results indicated that annual ET between 390 mm and 503 mm for the period. Using the eddy covariance

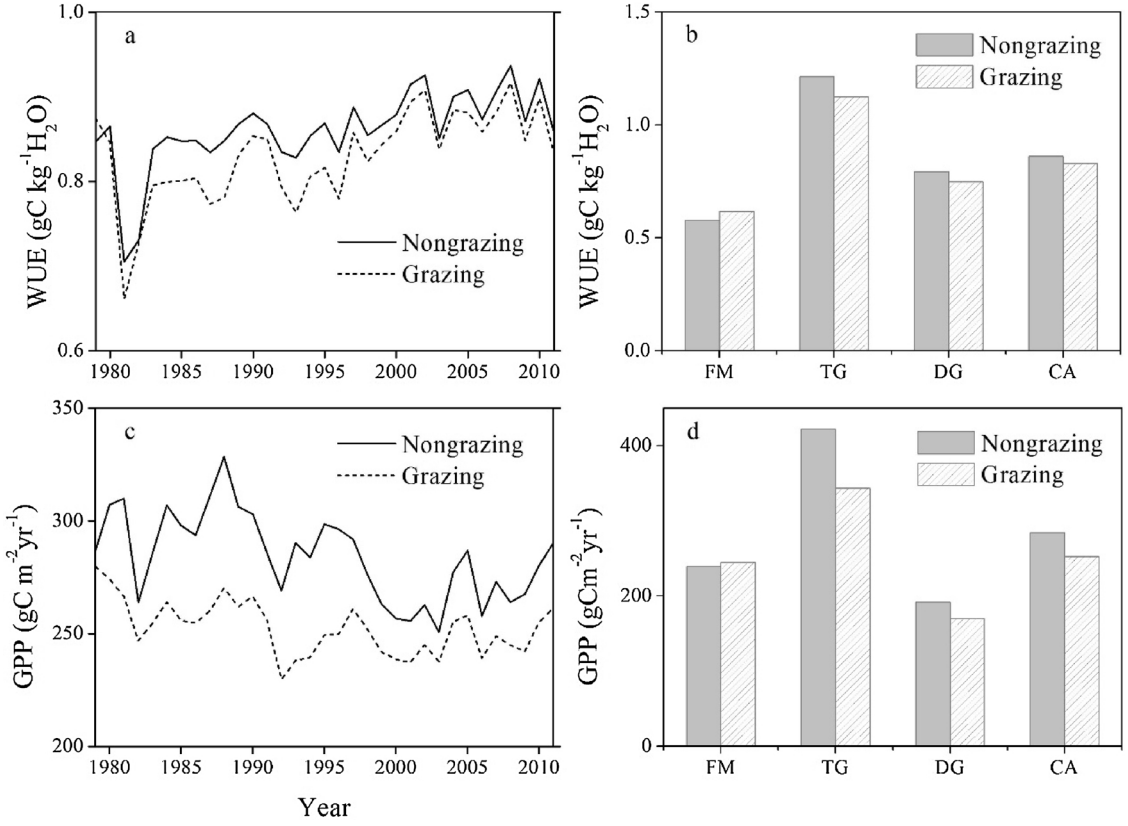

Fig. 8. Comparison of WUE (a, b) and GPP (a, b) under "Non-grazing" and "Grazing" scenarios in Central Asia between 1979 and 2011.

technique, Yang and Zhou (2011) estimated the cumulative ET over a temperate desert steppe in Inner Mongolia, China in 2008 was 150.9 mm. In 2006, using the eddy-covariance technique, Miao et al. estimated ET to be 230.3 mm and 201.4 mm for a fenced and a degraded steppe in Xilinhot, Inner Mongolia, China (Miao et al., 2009).

On average, grazing reduced ET for grasslands in Central Asia by 7.46% during the period 1979–2013 compare to Non-grazing scenario, with grazing similarly affecting the ET of different grassland ecosystems. Bremer et al. (2001) reported that grazing reduced the seasonal evaporation of a steppe in Kansas by 6.1% from May to October in 1999. Frank (2003) reported a 7% decrease in ET on average for a grazed prairie in three consecutive years although in the year with higher soil water availability, ET was greater in the grazed prairie than in the un-grazed prairie. Stewart and Verma (1992) found similar ET in both degraded and fenced steppes in wet years when soil moisture was not a limiting factor. Coronato and Bertiller (1996), on the other hand, reported that grazing failed to exert any effect on soil water content. Further studies, especially those at multiple sites and over a longer term, are required to better understand these different results.

4.3. WUE and grazing effects

Different plant species vary in their water use efficiency (Brümmer et al., 2012; Eichelmann et al., 2016; Singh et al., 2017; Tian et al., 2010). In our study, we found that the WUE of the three grassland ecosystems ranged from 0.62 g C kg^{-1} H_2O in FM to 1.12 g C kg^{-1} H_2O in TG, with an average of 0.83 g C kg^{-1} H_2O. (Law et al., 2002), calculated WUE for grassland was 0.94 g C kg^{-1} H2O based on the synthesis data from FLUXNET. Peng et al. (2007) used an integrated process-based ecosystem model (Dynamic Land Ecosystem Model, DLEM) to simulate WUE for different biomes, and the results indicated that average WUE in grassland in the southern United States was 0.58 g C kg^{-1} H_2O.

Our investigations indicated that grazing intensity significantly affected WUE in the three types of grassland. In general, the more a region was grazed, the more WUE decreased, thereafter declining as grazing intensified. This held true except for FM which increased markedly under low grazing intensity (Figs. 7 and 8). In particular circumstances, grazing intensity increases in WUE might be related to over-compensation in photosynthetic growth, which means plants can re-grow to an equal or greater biomass following defoliation (Agrawal, 2000; McNaughton et al., 1997; Olejniczak, 2011). In this study, negative relationships were found between WUE and evapotranspiration (Fig. 4b). A similar negative relation between WUE and ET was reported by Qiu et al. (2008) in the North China Plain. Using a multiple transect field survey, Wu et al. (2013) concluded that, in a certain time, an optimal grazing exclusion would influence the water–carbon process at the community level by changing species assemblage. These results indicated that it was possible to maintain relatively high yield and optimal WUE by refining the grazing regime.

5. Conclusions

In summary, this study attempted to fully assess the long-term changes of ET and WUE with the goal of understanding the interactions between carbon and water resources under grazing at the regional scale in Central Asian grasslands. Our results showed that, throughout Central Asia, annual ET decreased 1.47–2.72 mm per decade for the three grassland types during the period 1979–2011 while WUE exhibited increasing trends in at a rate of 0–0.006 g C kg^{-1} H_2O yr^{-1}. An increase in GPP was primarily responsible for the increase in WUE, likely attributable to more rapid plant growth as a consequence of changes in the environment such as increasing CO_2 as well as proper grazing. For the various grassland types, ET and WUE displayed differences and exhibited varying responses to grazing.

Grazing lowered ET by 7.47% in Central Asia from 1979 to 2011,

with 3.10%, 12.70% and 7.42% for FM, TG and DG, respectively. WUE increased by 6.86% for FM from non-grazed to grazed scenario, but decreased by 7.27% and 5.61% for TG and DG. Water use efficiency defines how efficiently the landscape uses precipitation to produce biomass and it has the potential to play an important role in setting pricing for ecosystem services (Palmer and Yunusa, 2011). Our findings imply that keeping a proper grazing intensity is essential to maintaining the water–carbon balance on dry grasslands. Grazing enclosures, therefore, are effective measures for maintaining dry grassland stability and improving resistance to potential climate changes.

Acknowledgements

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